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(54) **SPATIAL DOMAIN OPTIMAL ELECTRIC AND HYBRID ELECTRIC VEHICLE CONTROL WITH PATH FORECASTING**

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(57) **ABSTRACT**

A vehicle engine, electric machine and battery are operated, in certain examples, such that a predetermined route is segmented based on varying criteria to determine target battery state of charge at the segment endpoints along the route. The endpoints are a superposition of endpoints defined by predicted powertrain operating mode transitions, predicted vehicle acceleration transitions or predicted road grade transitions along the route.

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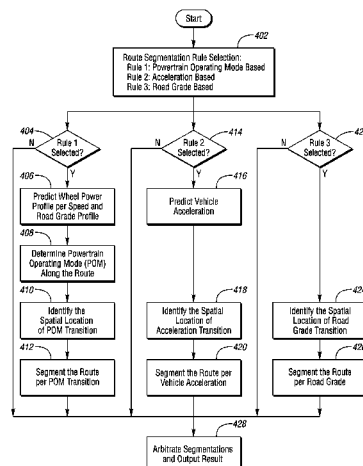
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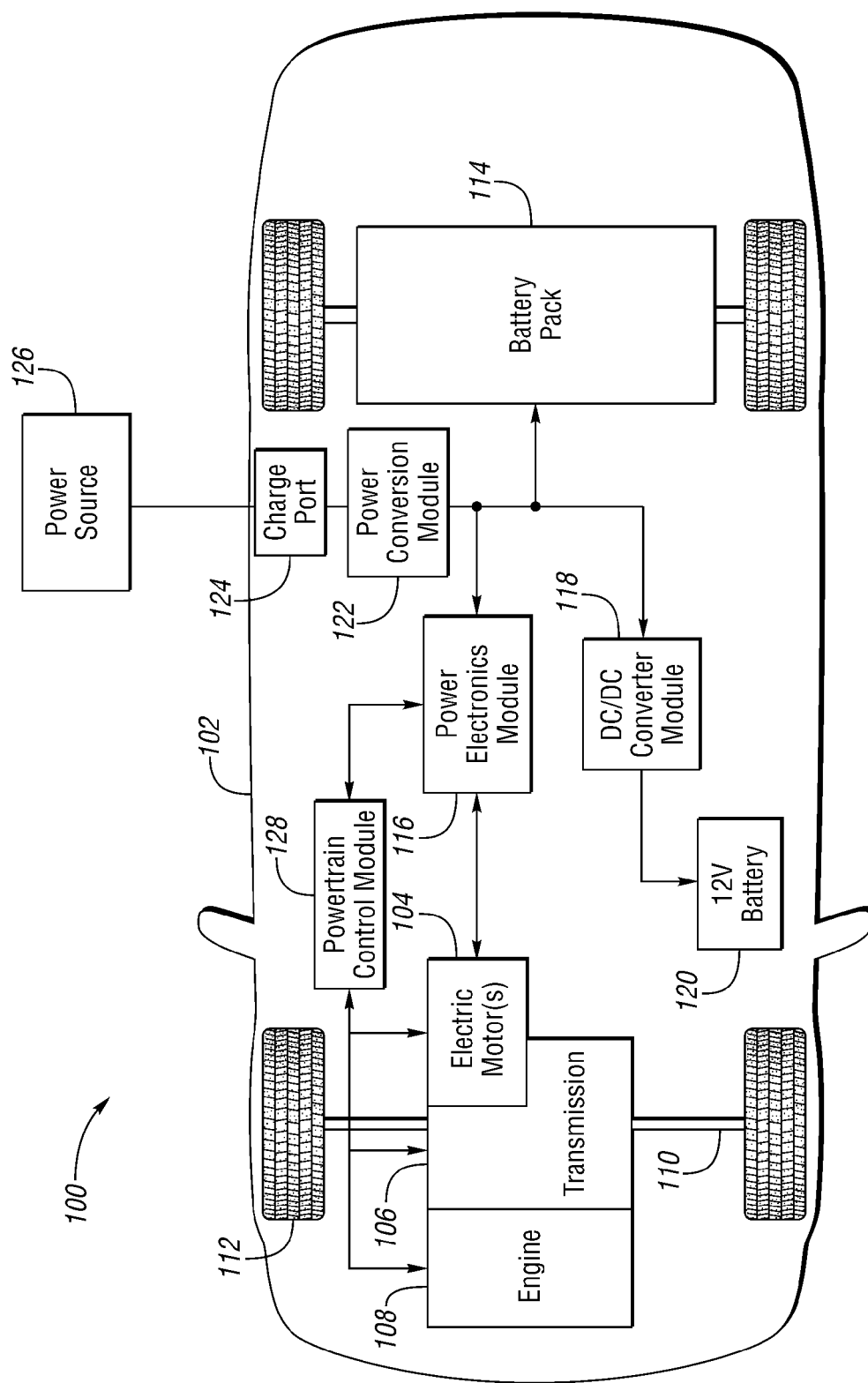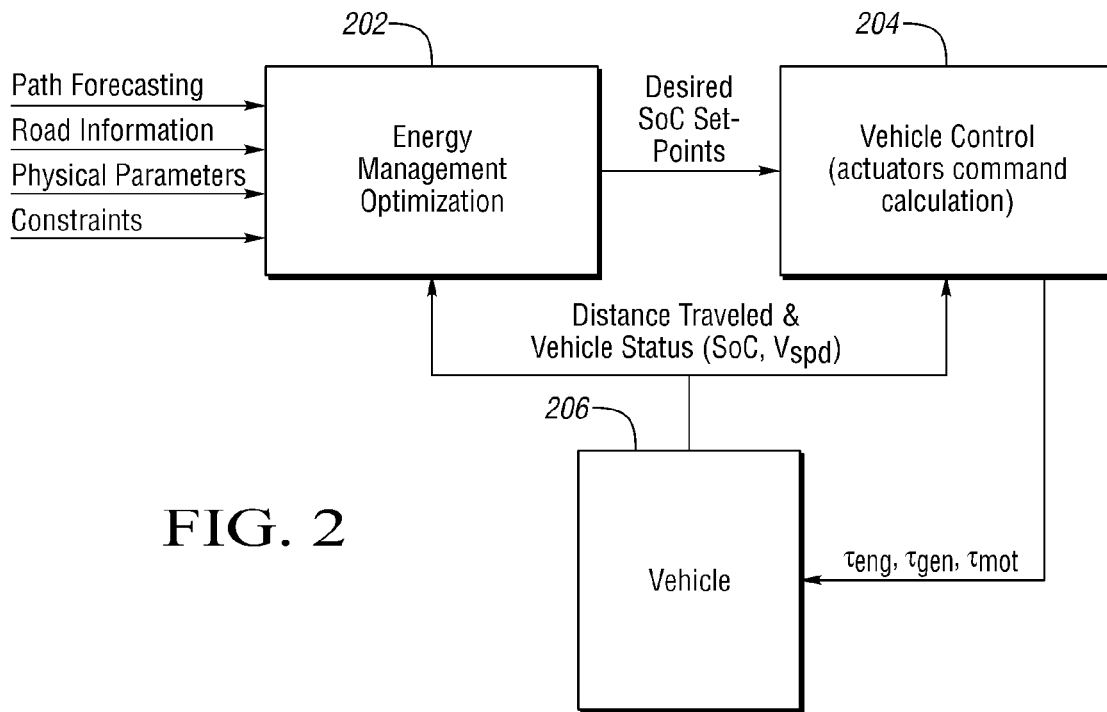
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FIG. 1

Path Forecasting →

Road Information →

Physical Parameters →

Constraints →

202 —

Energy
Management
Optimization

Desired
SoC Set-
Points →

204 —

Vehicle Control
(actuators command
calculation)

Distance Traveled &
Vehicle Status (SoC, V_{spd})

206 —

Vehicle

τ_{eng}, τ_{gen}, τ_{mot} →

FIG. 2

Start

↓

Read Inputs of Given Route
e.g. Vehicle Speed Profile
Road Grade Profile

302

↓

Route
Segmentation

304

↓

Spacial
Domain Optimization

306

↓

Output Desired
Battery SOC Setpoints

308

FIG. 3

Start

402
Route Segmentation Rule Selection:
Rule 1: Powertrain Operating Mode Based
Rule 2: Acceleration Based
Rule 3: Road Grade Based

404
N — Rule 1 Selected? — Y

414
N — Rule 2 Selected? — Y

422
N — Rule 3 Selected? — Y

406
Predict Wheel Power Profile per Speed and Road Grade Profile

416
Predict Vehicle Acceleration

408
Determine Powertrain Operating Mode (POM) Along the Route

410
Identify the Spatial Location of POM Transition

418
Identify the Spatial Location of Acceleration Transition

424
Identify the Spatial Location of Road Grade Transition

412
Segment the Route per POM Transition

420
Segment the Route per Vehicle Acceleration

426
Segment the Route per Road Grade

428
Arbitrate Segmentations and Output Result

FIG. 4

FIG. 5

Start

Read:
- Segmentation Input
- Rules Used in Segmentation
- Inputs of Given Route
502

Need Refinement on the Segmentation for Fuel Consumption Estimation? *504*
N

Y

Select Refinement Rules Further Divide Segment into Sub-segments *508*

Fuel Consumption Estimation *506*

Perform Optimization and Determine Battery Desired SOC Setpoints *510*

FIG. 6

Vehicle Speed *602*

SoC_0
608
SoC_1
SoC_2
608
SoC_3 *606*
SoC_4
SoC_5 *606*
SoC_D

Spatial Location *604*

SPATIAL DOMAIN OPTIMAL ELECTRIC AND HYBRID ELECTRIC VEHICLE CONTROL WITH PATH FORECASTING

TECHNICAL FIELD

The present disclosure is related to the management of fuel consumption in a hybrid electric vehicle.

BACKGROUND

A Hybrid Electric Vehicle (HEV) operates by buffering fuel energy by using the internal combustion engine to turn a generator; the electricity generated is stored in a battery. HEV systems can also recover kinetic energy by using the momentum of the vehicle to turn the generator; the electricity generated is then stored in a battery. Fuel is the predominate source of energy in an HEV system. Plug-in Electric Hybrid Vehicles (PHEVs) are an extension of existing hybrid electric vehicles (HEVs) with added energy flexibility. A PHEV utilizes a larger capacity battery pack than a standard HEV and the PHEV has two sources of energy, fuel and electricity from the electric utility grid.

An objective of the HEV control system is to minimize energy operational costs and emissions without compromising the vehicle drivability and system constraints. A standard Energy Management Control (EMC) strategy is traditionally designed to operate the HEV in electric drive mode in which the vehicle is operating only the electric motor to maximize the battery power output in blended operation mode, which is when the vehicle is operating both the engine and the electric motor.

SUMMARY

A hybrid electric vehicle may include a powertrain and at least one controller. The at least one controller may operate the powertrain according to a battery state of charge profile of a predetermined route determined by predictive route segmentation based on predicted powertrain operating mode transitions, acceleration transitions or road grade transitions.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates an example hybrid-electric vehicle with a powertrain control module;

FIG. 2 is a path forecasting based energy management control system flow diagram;

FIG. 3 is a flow chart of a spatial domain optimal hybrid control system with path forecasting;

FIG. 4 is a rule based route segmentation flow chart for a spatial domain optimal hybrid control system;

FIG. 5 is a spatial domain optimization flow chart for a spatial domain optimal hybrid control system;

FIG. 6 illustrates an example segmentation of a predetermined route.

DETAILED DESCRIPTION

Embodiments of the present disclosure are described herein. It is to be understood, however, that the disclosed embodiments are merely examples and other embodiments can take various and alternative forms. The figures are not necessarily to scale; some features could be exaggerated or minimized to show details of particular components. Therefore, specific structural and functional details disclosed herein are not to be interpreted as limiting, but merely as a

representative basis for teaching one skilled in the art to variously employ the present invention. As those of ordinary skill in the art will understand, various features illustrated and described with reference to any one of the figures can be combined with features illustrated in one or more other figures to produce embodiments that are not explicitly illustrated or described. The combinations of features illustrated provide representative embodiments for typical applications. Various combinations and modifications of the features consistent with the teachings of this disclosure, however, could be desired for particular applications or implementations.

FIG. 1 depicts an example of a plug-in hybrid-electric vehicle. A plug-in hybrid-electric vehicle 102 may comprise one or more electric motors 104 mechanically connected to a hybrid transmission 106. In addition, the hybrid transmission 106 is mechanically connected to an engine 108. The hybrid transmission 106 may also be mechanically connected to a drive shaft 110 that is mechanically connected to the wheels 112. The electric motors 104 can provide propulsion when the engine 108 is turned on. The electric motors 104 can provide deceleration capability when the engine 108 is turned off. The electric motors 104 may be configured as electric generators and can provide fuel economy benefits by recovering energy that would normally be lost as heat in the friction braking system. The electric motors 104 may also reduce pollutant emissions since the hybrid electric vehicle 102 may be operated in electric mode under certain conditions.

The traction battery or battery pack 114 stores energy that can be used by the electric motors 104. A vehicle battery pack 114 typically provides a high voltage DC output. The battery pack 114 is electrically connected to a power electronics module 116. The power electronics module 116 is also electrically connected to the electric motors 104 and provides the ability to bi-directionally transfer energy between the battery pack 114 and the electric motors 104. For example, a typical battery pack 14 may provide a DC voltage while the electric motors 104 may require a three-phase AC current to function. The power electronics module 116 may convert the DC voltage to a three-phase AC current as required by the electric motors 104. In a regenerative mode, the power electronics module 116 will convert the three-phase AC current from the electric motors 104 acting as generators to the DC voltage required by the battery pack 114. The methods described herein are equally applicable to a pure electric vehicle or any other device using a battery pack.

In addition to providing energy for propulsion, the battery pack 114 may provide energy for other vehicle electrical systems. A typical system may include a DC/DC converter module 118 that converts the high voltage DC output of the battery pack 114 to a low voltage DC supply that is compatible with other vehicle loads. Other high voltage loads, such as compressors and electric heaters, may be connected directly to the high-voltage bus from the battery pack 114. In a typical vehicle, the low voltage systems are electrically connected to a 12V battery 120. An all-electric vehicle may have a similar architecture but without the engine 108.

The battery pack 114 may be recharged by an external power source 126. The external power source 126 may provide AC or DC power to the vehicle 102 by electrically connecting through a charge port 124. The charge port 124 may be any type of port configured to transfer power from the external power source 126 to the vehicle 102. The charge port 124 may be electrically connected to a power conversion module 122. The power conversion module may con-

dition the power from the external power source **126** to provide the proper voltage and current levels to the battery pack **114**. In some applications, the external power source **126** may be configured to provide the proper voltage and current levels to the battery pack **114** and the power conversion module **122** may not be necessary. The functions of the power conversion module **122** may reside in the external power source **126** in some applications. The vehicle powertrain including engine, transmission, electric motors, electric generators and power electronics may be controlled by a powertrain control module (PCM) **128**.

In addition to illustrating a plug-in hybrid vehicle, FIG. **1** can illustrate a battery electric vehicle (BEV) if component **108** is removed. Likewise, FIG. **1** can illustrate a traditional hybrid electric vehicle (HEV) or a power-split hybrid electric vehicle if components **122**, **124**, and **126** are removed.

Path forecasting and path information for a given route can be used to optimize fuel economy of a HEV by scheduling the battery State of Charge (SOC) setpoints along the route. One strategy for this optimization can be performed by viewing the overall route, optimizing each point on a route and providing a signal based on the optimized operation to the Powertrain Control Module (PCM).

One method of scheduling the battery SOC setpoints along the route is a path dependent receding horizon control for real-time HEV energy management. This allows the system to obtain the optimal battery SOC scheduling by minimizing a cost function which represents the fuel consumption for predicted drive conditions for the intended route. FIG. **2** illustrates one method of decomposing the optimal HEV control problem into two levels. The high level control (Energy Management Optimization **202**) determines controls such as the desired setpoints for the battery SOC along the route based on inputs including but not limited to path forecasting, road information, physical parameters, and general system constraints. The low level control (Vehicle Control **204**) tracks the battery SOC setpoints and generates the desired vehicle operation parameters (for example battery system power, engine power, rotational engine speed, and engine operation). These intermediate variables allow the Vehicle Control **204** to calculate the torque commands which are sent to the Vehicle **206** and more specifically sent to control the engine and electric machines and provide feedback of the vehicle status resulting in improved fuel economy. The requested torques (engine torque τ_{eng}, generator torque τ_{gen}, and motor torque τ_{mot}) are communicated to the Vehicle **206** and the vehicle operation data is fed back to at least the Energy Management Optimization **202** and the Vehicle Control **204**. The vehicle operation data includes but is not limited to vehicle speed V_{spd}, battery state of charge SOC and distance traveled.

A method to optimize the fuel consumption may require an amount of computation that is greater than the computation bandwidth available in the embedded control module. One method of resolving this computational deficient may be accomplished off-line using a more powerful remote computer system to calculate the optimal operation. It may be desirable to implement this control algorithm real-time. A real-time implementation can include an embedded control module that predicts and processes traffic, road information and driver inputs and collects current vehicle status (battery SOC, vehicle speed, etc.). This real-time implementation collects and processes the data such that the processing is without buffering delays and in which the output is representative and adaptive to the real driving conditions.

For real-time implementation of such an optimization, it may not be practical to determine the SOC setpoint for every

moment in time of the route because of the extensive computation requirements. One method of solving this is to divide the route into segments. An example method of dividing the route is to time divide the route based on available computational bandwidth. One problem with this is that it does not account for characteristics of the route. Another example method is to decompose the route into segments that have similar characteristics and attributes. Then, the SOC setpoint can be scheduled for the end point of each segment based on the optimization. The second example of route segmentation shows advantages in generating a real-time fuel consumption estimation method for a given route segment.

FIG. **3** is a flow chart illustrating the overall flow to determine the desired battery SOC setpoints as used to control the electric motor(s) **104** and electric machine(s). This flow chart typically resides in the powertrain control module **128**, and may be used for Energy Management Optimization **202**. Block **302** is a data input block in which route preview information including but not limited to vehicle speed, road grade, traffic data, route information (traffic signs, traffic lights, posted speed limits) are input to block **302**. The input route is then segmented in block **304**. This segmentation may be based on user data, predicted data, or information provided wirelessly by the internet network and cloud computing. After the route is segmented, a spatial domain optimizer **306** may be used to schedule desired battery SOC setpoints by minimizing estimated fuel consumption along the route. The output of block **306** is the desired battery SOC setpoints as shown in **308** which may be used by the Vehicle Control **204** to control the electric machine(s) and electric motor(s) **104**.

FIG. **4** is the subroutine used in block **304**. FIG. **4** is a rule based route segmentation flow chart used to decompose the route. Block **402** determines which rules will be used to determine the segmentation. Depending on the computational power capability available in the controller and other factors, the route can be segmented based on one, two, or all three rules. The resulting segmentations are arbitrated to determine the segmentation for the spatial domain optimization.

Rule 1 is the powertrain operating mode based rule which is selected in block **404**. In this rule, the route is divided based on a change in the powertrain operating mode. The objective is to separate when the engine is off, such as in the electric vehicle mode from when the engine is on, such as in the hybrid electric vehicle mode. The result is that there is no blended powertrain operation mode such as a combination of electric vehicle mode and hybrid modes in a discrete route segment.

In rule 1, the wheel power profile is calculated in block **406** using data including vehicle speed, road grade profile, traffic data and other road characteristics such as traffic lights, traffic signs, posted speed limits, freeway ramps, etc. The predicted wheel power profile calculated in **406** is used to determine the powertrain operating mode (POM) in block **408**. The POM is mapped with the spatial location in block **410** and the route is segmented in block **412** according to the POM. The powertrain mode requires at a minimum the predicted wheel power demand and vehicle speed which are the primary parameters used in the engine start or stop request determination in the low level controller. The powertrain mode change points are reasonable control points of a battery SOC. No blended mode operation within one segment is required to remain substantially constant to allow an average to be calculated based on the fuel consumption estimation for the energy management optimization. This

powertrain mode based segmentation allows for the optimized SOC setpoints to be tracked by the low level controller.

Rule 2 is an acceleration based rule which is selected in block **414**. In this rule, the predicted change of acceleration is used to decompose the route. If the change is above a pre-defined and calibrateable threshold, a respected spatial location of the acceleration change is identified and used for the segmentation. The predicted vehicle acceleration is performed in block **416** using vehicle speed which can be derived from data input to block **402**. The predicted vehicle acceleration is mapped with the spatial location in block **418** where transitions in the vehicle acceleration are identified. The vehicle acceleration transitions are defined by criteria including static and dynamic thresholds, these thresholds include but are not limited to a vehicle acceleration (i.e. >0.5 fps^2), a percentage vehicle acceleration change (i.e. >5%) or a combination of these criteria or other criteria including vehicle speed (i.e. >0.5 fps^2 @ 0-20 mph). Based on the vehicle acceleration transitions, the route is segmented in block **420**. This rule can be easily extended to identify route segments with standstill vehicle speed only.

Rule 3 is a road grade based rule which is selected in block **422**. In this rule, the segmentation is based on road segments which have a substantially similar road grade. If the road grade change is above a pre-defined and calibrateable threshold, a respected spatial location of the road grade transition is identified in block **424**. The road grade transitions are defined by criteria including static and dynamic thresholds, these thresholds include but are not limited to a road grade (i.e. >0.05%), a percentage road grade change (i.e. >5%) or a combination of these criteria or other criteria including vehicle speed (i.e. >0.05% @ 0-20 mph). Based on the road grade transitions, the route is segmented in block **426**. The road grade change is determined by either the road grade itself or the derivative of the road grade. The road grade can be used when piecewise constant road grade along the route is provided. The derivative of road grade can be used when the road grade provided is more dynamic.

With the use of multiple rules, the results of these rules are forwarded to block **428** where arbitration is used to determine the segmentation, which is forwarded to the spatial domain optimization block **306**. The arbitration may superimpose the results of one rule with the results of other rules such that common points are represented once as well as each individual point generated by either rule. The resultant superposition, which arises from the act of superposing, allows for the capture of all points identified by the rules to be used for segmentation. For example, if Rule 2 identifies points "A" and "B" and Rule 3 identifies points "B" and "C," a superposition of these points will result in a route segmented by points "A," "B" and "C." Rule 2 and 3, which are points of change of acceleration or road grade can be identified between adjacent route segments, which are reasonable locations for SOC control points. In addition, each route segment will have relatively consistent acceleration and road grade, therefore consistent engine operating and fuel flow rate. This is necessary to guarantee the accuracy of average power based real-time fuel consumption estimation.

Although FIG. **4** illustrates 3 rules, other factors can be considered to segment the route. The other factors include a minimum engine on time used to restrict the minimum length of the HEV segment, a reduction in the total number of route segments used in the optimization or a minimum length of each segment.

The optimization can be formulated to minimize the fuel consumption along the route using Dynamic Programming

(DP). The nonlinear DP problem is solved using the state and control variables (which are the battery SOC at the beginning and the end of each segment). The state of control variables are quantized into a finite grid in which the fuel consumption is estimated at these SOC grid points for each segment. The fuel consumption estimation of each segment is essential to DP optimization. Segmentation affects the accuracy of the fuel consumption estimation; ideally segmentation for fuel estimation may be used for optimization. However, using the same segmentation for both optimization and fuel consumption estimation may increase the number of segments, which will increase the computation power requirement exponentially in DP optimization. A solution to the conflict of the computation power requirement and the fuel consumption estimation accuracy is when the segmentation for optimization is used as the base for fuel consumption estimation with a subsequent stage of fuel consumption estimation. If a segment's accuracy is not acceptable for fuel consumption estimation, a further refinement generating sub-segments can be performed with the total fuel consumption estimate for the segment being the sum of the estimates for the sub-segments. This strategy will improve the accuracy of the fuel consumption estimation without increasing computation power requirements because the number of segments for DP optimization is not increased.

FIG. **5** is a spatial domain optimization flow chart which resides in block **306**. Route segmentation and route segmentation rules used in FIG. **4** are received in block **502**. Block **504** decides if the current segment can be used to calculate the fuel consumption estimation for that segment. If it is determined that fuel consumption can be calculated accurately using the current segmentation, the fuel consumption is then calculated in block **506**. If it is determined that the fuel consumption is not able to be calculated using the current segmentation, additional refinement rules are provided and the route segments are analyzed to determine if each current segment can be divided into sub-segments in block **508**. Once the fuel consumption estimation is determined in block **506**, the spatial domain optimization is performed and battery SOC setpoints are determined in block **510**. The output of the optimization is the desired battery SOC setpoints at the end of each segment. In contrast to instantaneous time based optimization, this optimization is referred as spatial domain optimization because the segmentation is spatial domain based.

FIG. **6** is a graph of vehicle speed **602** with respect to a geographic or spatial location **604**. In this illustration, a predetermined route is divided into segments based on vehicle speed inflection criteria and may relate to a segment start or endpoint **606**. If the segment is divided into sub-segments as illustrated in FIG. **5**, additional sub-endpoints or sub-segments **608** can be included or superimposed upon the original segmentation to improve the accuracy.

Conventional HEVs buffer fuel energy and recover kinematic energy in electric form to improve the overall vehicle system operating efficiency. The fuel is the only energy source. For PHEVs, there is an additional source of energy—the amount of electric energy deposited in the battery from the grid during battery charge events. A power management strategy for PHEVs has the potential to allocate the drive power demand between the two energy sources to achieve better fuel economy or improved drivability while still satisfying the other objectives. While conventional HEVs are operated to maintain the battery state of charge (SOC) around a constant level, PHEVs use as much pre-saved battery electric (grid) energy as possible before the

next battery charge event, i.e., it is desirable to fully use the relatively cheap grid supplied electric energy after each plug-in charge event. After the battery SOC depletes to a lowest conservative level, the PHEV operates as a conventional HEV operating about the lowest conservative level for the battery.

The processes, methods, or algorithms disclosed herein can be deliverable to/implemented by a processing device, controller, or computer, which can include any existing programmable electronic control unit or dedicated electronic control unit. Similarly, the processes, methods, or algorithms can be stored as data and instructions executable by a controller or computer in many forms including, but not limited to, information permanently stored on non-writable storage media such as ROM devices and information alterably stored on writeable storage media such as floppy disks, magnetic data tape storage, optical data tape storage, CDs, RAM devices, FLASH devices, MRAM devices and other magnetic and optical media. The processes, methods, or algorithms can also be implemented in a software executable object. Alternatively, the processes, methods, or algorithms can be embodied in whole or in part using suitable hardware components, such as Application Specific Integrated Circuits (ASICs), Field-Programmable Gate Arrays (FPGAs), state machines, controllers, or any other hardware components or devices, or a combination of hardware, software and firmware components.

While exemplary embodiments are described above, it is not intended that these embodiments describe all possible forms encompassed by the claims. The words used in the specification are words of description rather than limitation, and it is understood that various changes can be made without departing from the spirit and scope of the disclosure. As previously described, the features of various embodiments can be combined to form further embodiments of the invention that may not be explicitly described or illustrated.

While various embodiments could have been described as providing advantages or being preferred over other embodiments or prior art implementations with respect to one or more desired characteristics, those of ordinary skill in the art recognize that one or more features or characteristics can be compromised to achieve desired overall system attributes, which depend on the specific application and implementa-

tion. These attributes can include, but are not limited to cost, strength, durability, life cycle cost, marketability, appearance, packaging, size, serviceability, weight, manufacturability, ease of assembly, etc. As such, embodiments described as less desirable than other embodiments or prior art implementations with respect to one or more characteristics are not outside the scope of the disclosure and can be desirable for particular applications.

What is claimed is:

1. A vehicle comprising:
   a battery;
   an engine;
   an electric machine; and
   a controller programmed to, for each of a plurality of route segments having an endpoint defined by a location and a target battery state of charge (SOC), operate the engine and electric machine to achieve the target battery SOC, wherein the endpoints are a superposition of a first set of predicted engine on/off route transition points and a second set of predicted vehicle acceleration route transition points that is derived independently of the first set.

2. The vehicle of claim 1, wherein the endpoints are further a superposition of a third set of predicted road grade route transition points derived independently of the first and second sets.

3. A control system comprising:
   a controller programmed to, for each of a plurality of route segments having an endpoint defined by a location and a target battery state of charge (SOC), operate a powertrain to achieve the target battery SOC, the endpoints being a superposition of a first set of predicted engine on/off route transition points and a second set of predicted vehicle acceleration route transition points that is derived independently of the first set.

4. The system of claim 3, wherein the endpoints are further a superposition of a third set of predicted road grade route transition points derived independently of the first and second sets.

5. The system of claim 3, wherein each of the segments includes a superposition of sub-endpoints based on a fuel consumption estimation for the segment.

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